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EFFECT OF SHRAPNEL PENETRATION ON LITHIUM-CARBON MONOFLUORIDE AND LITHIUM-MANGANESE DIOXIDE BATTERIES

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Effect of Shrapnel Penetration on Lithium-Carbon Monofluoride and Lithium-Manganese Dioxide Batteries

W.N.C. Garrard

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Abstract

National BR2/3A lithium-carbon monofluoride and Duracell DL2/3A lithium-manganese dioxide batteries were subjected to simulated shrapnel penetration using a projectile from an M16 rifle. Trials were conducted on batteries in various states of charge (0%, 50% and 100% discharged) in both wet and dry environments. Only one fully charged Duracell battery (under wet conditions) caught fire during the tests. The effects of environmental conditions, the chemical reactions involved, and the state of charge of the batteries on the probability of the batteries igniting are discussed.

MATERIALS RESEARCH LABORATORY

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Cordite Avenue, Maribyrnong
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Fax: (03) 318 4536

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1. *Introduction*

Two types of lithium battery, Duracell DL2/3A and National BR2/3A, are being considered by the Royal Australian Navy as the power source for personnel locator beacons fitted to Navy aircrew life-jackets. These batteries possess characteristics, such as shelf-life, energy density, power density and reliability in use, which are superior to those of the mercury oxide batteries presently in service. However, lithium batteries, particularly those containing sulphur dioxide and thionyl chloride, are considered to be more sensitive to physical or electrical abuse [1]. Although safety devices fitted to lithium batteries and the education of users to the proper handling procedures lower the risk of an incident, there appear to be no reports other than manufacturers' literature [2, 3] on the hazards associated with the effect of penetrating the battery case.

National [2] subjected fully charged and 50% discharged lithium-carbon monofluoride batteries to drill and crush tests. During the latter test the batteries were crushed with a hammer to half their original diameter, which resulted in a decrease in cell voltage, an increase in temperature (maximum temperatures ranged from 149 to 175°C), and the leakage of electrolyte from the battery. Drill tests (4 mm drill bit at 500 or 2800 r/min) also resulted in a decrease in voltage and an increase in temperature (66 to 144°C). Lithium-manganese dioxide batteries manufactured by Duracell, state of charge unknown, were subjected to penetration, crush, and saw tests [3]. Penetration tests were conducted by inserting a spike (18.5 mm long × 1.65 mm diameter) to various depths, while batteries in the crush test were compressed with a vice, pliers or a household garbage compactor. No fires or explosions occurred during these tests.

Neither manufacturer indicated the amount of energy transferred to the batteries during these tests, although one would expect the amount to be relatively small. Thus, the above evaluations may not reflect the effect of shrapnel penetrating the battery case where the energy transferred to the battery would be large. This paper reports the results of battery penetration by shrapnel trials conducted using projectiles fired from an M16 rifle.

2. Experimental

Duracell DL2/3A lithı ım-manganese dioxide and National BR2/3A lithium-carbon monofluoride batteries were subjected to various assessments to ensure that they met the manufacturers' specifications. Figure 1 displays typical discharge curves for the batteries when they were discharged through 75 ohm resistors. For the shrapnel penetration tests, batteries were divided into three categories depending on their state of charge, namely fully charged, 50% discharged, and 100% discharged. Batteries in the 50% discharged category were brought to the required state by discharging them through 150 ohm loads for 15.57 h (Duracell) or 15.27 h (National), assuming a common cutoff voltage of 1.80 V. Fully discharged batteries were obtained by discharging the batteries through 150 ohm loads for a period of one week.

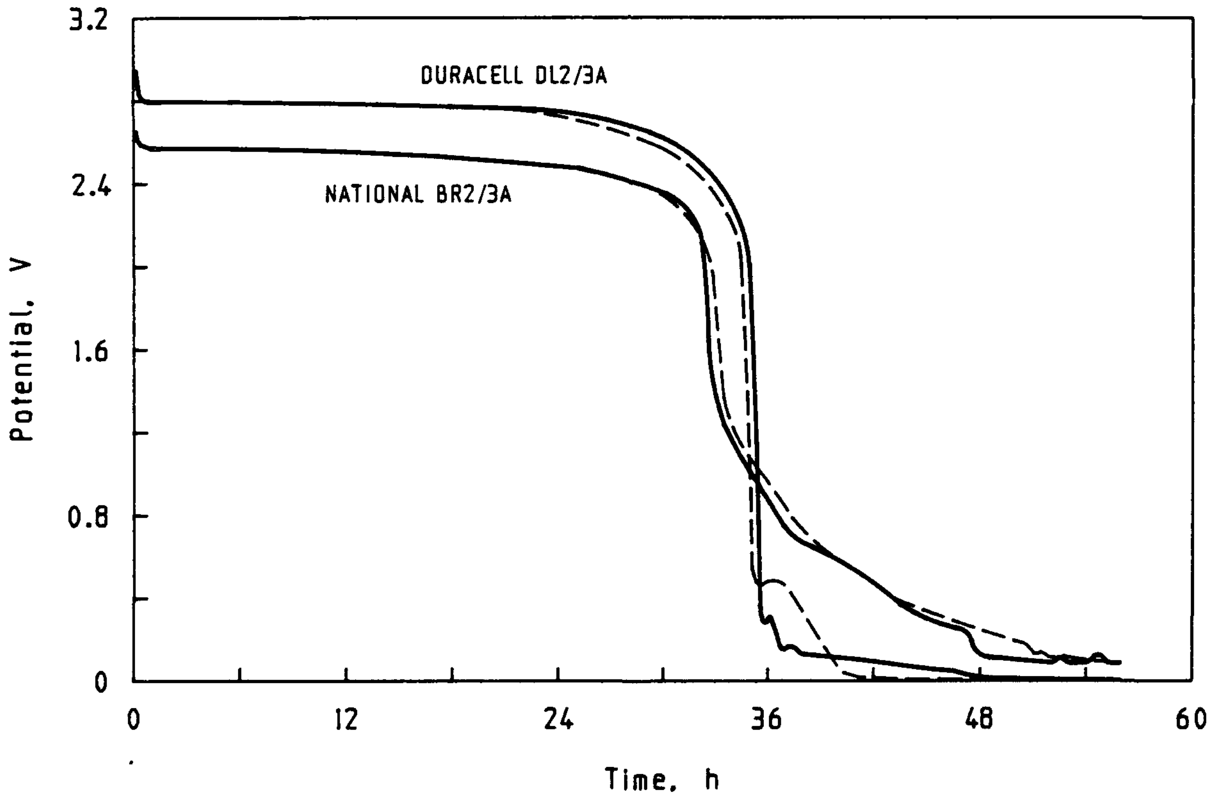

Figure 1: Duplicate discharge curves for (a) National BR2/3A and (b) Duracell DL2/3A batteries. Batteries were discharged through 75 ohm loads.

All batteries were mounted in a "U" clamp (Fig. 2a) which was mounted on a sturdy test rail. Also attached to the test rail were an M16 rifle (5.56 mm calibre) for firing the projectiles and a muzzle-flash baffle plate used to ensure the muzzle flash did not interfere with the penetration trials or the recording of the events on video tape. The distance between the rifle muzzle and the battery was 100 cm, while the baffle plate was situated 60 cm from the battery. The projectile was a tapered round with a mass of 3.55 g and a muzzle velocity of 968.5 m s^{-1}. Trials were conducted under dry and wet conditions within an ambient temperature range of 7 to 14°C. Water for the wet trials was supplied by a garden spray (Fig. 2) at a flow rate of 5.4 dm^3 min^{-1}. A full matrix of the test conditions is shown in the accompanying table. All events were recorded using conventional video equipment and one event from each position in the test matrix was also recorded using a Kodak SP2000 high speed video camera and recorder.[1]

Test matrix and results of battery penetration trials

Battery	National BR2/3A						Duracell DL2/3A					
Charge (%)[a]	100		50		0		100		50		0	
Environment[b]	w	d	w	d	w	d	w	d	w	d	w	d
No. tested	10	10	10	10	9	9	10	10	10	10	9	9
No. ignited	0	0	0	0	0	0	1	0	0	0	0	0

a. 100 = fully charged, 50 = half discharged, 0 = fully discharged.
b. w = wet, d = dry.

3. Results

The "as received" batteries displayed the characteristics of fully charged lithium batteries as set down in the manufacturers' literature. The final row in the table displays the number of batteries in each category which ignited during the trials.

Video footage indicated that after a projectile had penetrated a battery (both types at all states of charge) there was no chemical reaction between the contents of the battery and the dry environment. However, all fully charged batteries (both types) were much warmer to the touch than half discharged or fully discharged batteries after each trial, thus indicating that a chemical reaction had occurred in the batteries. No fires were observed for any trials conducted under dry conditions.

1 A video tape containing selected trials is available upon request.

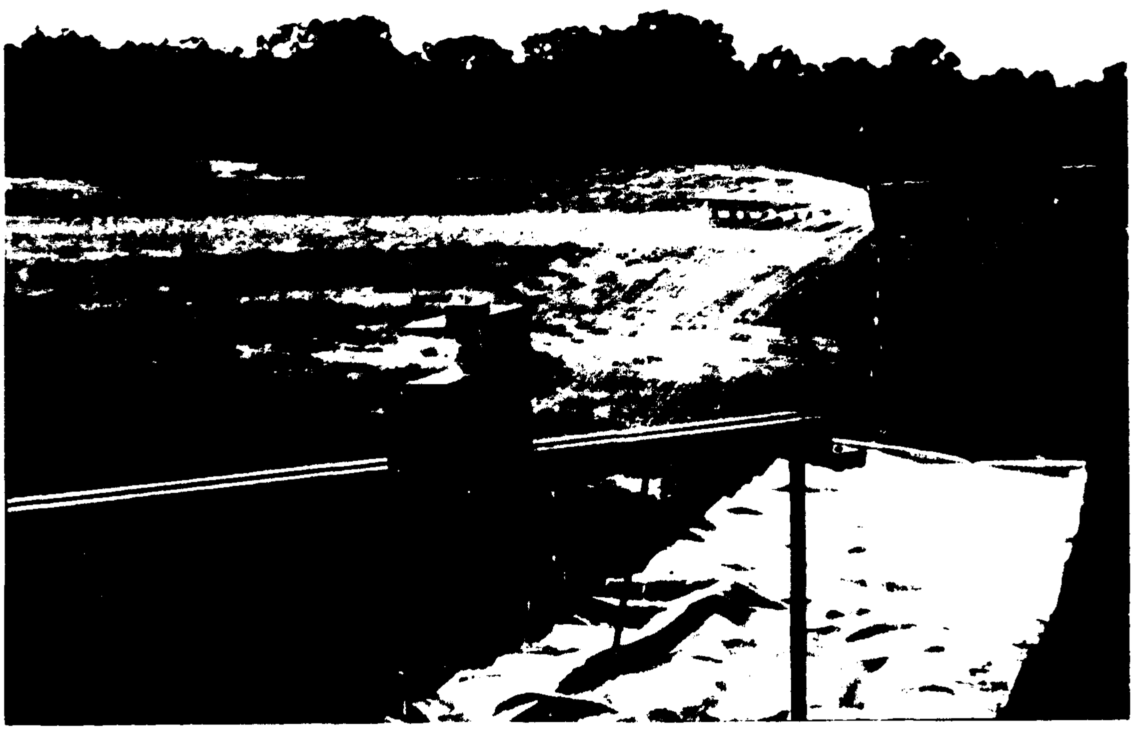

Figure 2: (a) Photograph of test rail. From left to right: M16 rifle, muzzle-flash baffle plate, "U" clamp, and garden spray. (b) Close-up photograph of "U" clamp and garden spray in operation.

In the wet environment, examination of the video footage showed that each battery emitted a small cloud of smoke immediately after exit of the projectile, and that there was vigorous reaction between any exposed lithium and water. It was impossible to gauge the temperature of the battery after the trial. Only one fully charged Duracell battery caught fire during the wet trials.

The high speed video footage did not indicate any difference in the fragmentation pattern for the two types of battery. However, physical inspection (Fig. 3) showed that almost all the Duracell batteries disintegrated on impact of the projectile, while the National batteries generally displayed a small entry hole and an exit hole approximately three times the diameter of the entry hole. The rust on the batteries in Figure 3 resulted from disposal of the batteries in water to destroy any residual lithium.

4. *Discussion*

National and Duracell batteries contain about 0.45 and 0.5 g of lithium, respectively, while γ-butyrolactone (National) and a mixture of 1,2-dimethoxyethane/propylene carbonate (Duracell) are used as the organic solvents. Both battery types are based on a spiral construction. The flash points for γ-butyrolactone, 1,2-dimethoxyethane and propylene carbonate are 99, 1 and 135°C respectively. No information is available concerning the flash point for a mixture of 1,2-dimethoxyethane/propylene carbonate, but, in general, the flash point for a mixture is biased in favour of the more volatile solvent (in this case 1,2-dimethoxyethane).

With both battery types containing similar amounts of lithium, it is expected that a similar quantity of heat will be generated in each manufacturer's battery by the reactions involving lithium and the impact of the projectile. Thus the only difference between the two types is in the flash points for the different solvents. Because of the lower flash point for the solvent in the Duracell battery, it would be anticipated that this system would be more prone to ignition than the National battery.

The trials indicated that the contents of both types of battery readily underwent a chemical reaction subsequent to penetration by a projectile, with batteries exposed to wet conditions being more reactive than those exposed to a dry environment. Lithium metal slowly reacts with water, oxygen and nitrogen at room temperature, but at higher temperatures the reactions are very vigorous [4]. At elevated temperatures, reaction between lithium and the organic material in the battery cannot be discounted. These chemical reactions could result in fires due to ignition of the lithium, hydrogen (produced by the reaction between water and lithium) or the flammable organic solvent in the battery. In fact, the video recording for the only battery that caught fire showed that two events took place: initially a burning fragment was ejected from the battery (most likely burning lithium) followed by the appearance of a light luminous flame around the battery (probably burning organic solvent).

a

b

Figure 3: Photographs of (a) Duracell DL2/3A and (b) National BR2/3A batteries after projectile penetration.

The charge state of each battery determines the amount of lithium present in the battery. Examination of the video footage for batteries (both types, wet conditions) in various charge states showed that the amount of reaction between lithium and water increased in the order: fully discharged, half discharged, fully charged. Hence the quantity of heat generated and the temperature increase also follow this pattern. Because ignition of the lithium or organic solvent in the battery is dependent upon the temperature of the battery, it is expected that the probability of ignition after puncture by shrapnel will be highest for fully charged batteries and lowest for fully discharged batteries.

The fragmentation of the battery may also be an important factor in determining whether or not a fire will occur. Punctured National batteries generally retained their cylindrical appearance, hence there was less exposure of the contents of the batteries to the atmosphere. This small exposure area may not have allowed the reactions to proceed at a sufficient rate to generate enough heat to ignite any components in the batteries. Alternatively, penetration of the Duracell batteries resulted in significant exposure of the contents within these batteries. Such a large exposed area would enhance the reaction rate between lithium and the atmosphere resulting in considerable heat generation and possibly fire. However, in the commercial battery pack used in the life-jackets, the individual batteries are encased in a resin which would tend to restrict the fragmentation of the batteries after any shrapnel had passed through the pack. Under these conditions it could be envisaged that the fragmentation pattern for both battery types would be similar and not play a major role in determining the possibility of battery pack ignition.

5. Conclusions

Although one Duracell battery did catch fire during the trials, it is not possible to conclude whether this result is statistically significant due to the small number of samples used in the tests. A larger sample population would indicate whether one battery type has a higher probability of ignition than the other.

However, based on the present data it would be reasonable to conclude that Duracell batteries may be slightly more prone to ignition and fire because these batteries contain an organic solvent mixture which should have a lower flash point. Regardless of manufacturer, fully charged batteries present a slightly greater risk of overheating/ignition than partly or fully discharged batteries, with the risk being greatest when the batteries are exposed to a wet environment.

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AUTHOR(S)

W.N.C. Garrard

CORPORATE AUTHOR

DSTO Materials Research Laboratory
PO Box 50
Ascot Vale Victoria 3032

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